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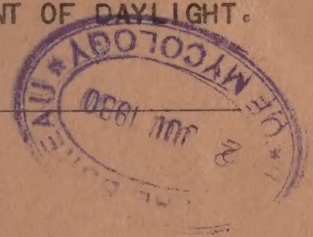
CONFERENCE OF EMPIRE METEOROLOGISTS, 1929.

AGRICULTURAL SECTION.

METHODS FOR THE PHOTO-ELECTRIC AND PHOTO-CHEMICAL MEASUREMENT OF DAYLIGHT.



BY

W.R.G. ATKINS, Sc.D., F.R.S.,

HEAD OF THE DEPT. OF GENERAL PHYSIOLOGY,

MARINE BIOLOGICAL LABORATORY, PLYMOUTH,

AND

H. H. POOLE, Sc.D.,

CHIEF SCIENTIFIC OFFICER, ROYAL DUBLIN SOCIETY.

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INTRODUCTION.

In a vegetational survey of the globe one can see how the idea of the importance of temperature dominates all other considerations. This is partly due to the fact that temperature is susceptible of accurate measurement ; in part the reason is anthropomorphic, and in addition there is a solid residuum of truth. In sharp contrast stands the meagre amount of information as to the amount of light received in various latitudes and throughout the year. While we have the Callendar Ångström, and other radiation recorders to measure the total energy no similar instrument has heretofore been available for measuring light alone.

[Recourse has been had to various photo-chemical methods and especially to photographic methods. A good summary of these has recently been given by Rübel (1928). A large number of measurements were made by Wiesner (1907) and his co-workers using silver-chloride paper allowed to darken to a standard tint as originally worked out by Bunsen and Roscoe. These include measurements made in both tropical and northerly latitudes. Lundegårdh (1925) very properly considers light before all other factors in his discussion on plant distribution. He also points out that measurements made according to the Bunsen formula $S = i.t$ (where S denotes the degree of darkening of the paper, i the intensity of illumination and t the time), are not correct, because the formula is not exact. This point has also been referred to by Klugh (1925), who considers that its neglect has invalidated all work done by this method. In view, however, of the great variations in light intensity found it seems unnecessary to condemn the careful comparative values thus obtained in so sweeping a manner. A direct comparison of the photographic paper and the photo-electric methods would undoubtedly be of value, especially as they both measure the violet end of the spectrum.

[Reference may also be made to the classical researches of Abbot and his co-workers (1922) upon the distribution of energy in the solar spectrum at various places and at all seasons, and to the data obtained and collected by Dorno (1919). Measurements of illumination are also given by Walsh (1923) and in the works of Luckiesh (1915, 1922).

The advent of the photo-electric cell, more especially the vacuum type, has placed in our hands an instrument of a considerable degree of precision; this we have used since 1924 for daylight photometry. Its use permits of the calibration of photo-chemical methods also. An outline of both the methods and their results is given in the following pages.

OPTICAL CONSIDERATIONS.

Attention was called in some of our earlier papers (1925, p.106 and 1926, 1, p.180) to the optical conditions affecting the use of photometers whose windows consist of perfectly diffusing plane discs. In the general problem of measuring daylight account must also be taken of reflected light travelling upwards, an important factor over snow or water. In a recent paper (1929, 5) this has been discussed in some detail and is now given in an abbreviated form.

V denotes the vertical illumination on a horizontal plane, V_s, V_d and V_r being, respectively, the vertical illuminations due to pure sunlight, diffuse light from the sky, and reflected light that would be received on an inverted window small enough not to shade the ground below appreciably. Hence $V = V_s + V_d$. Also $H = H_s + H_d + H_r$, since the horizontal light falling on a vertical surface, unlike the horizontal surface, receives reflected light.

M is the illumination on a surface set to catch the maximum flux of light. In the open, in absence of sunlight $M_d = V_d$. In sunlight the plane surface must be set nearly, but not quite, perpendicular to the sun's rays, the plane being always more nearly horizontal than the perpendicular, and markedly so when the sunlight is weak.

I, the total illumination, cannot be received directly on any single plane surface, but may be measured by a photometer whose absorbing surface is a complete sphere. It is defined as $\int_0^{4\pi} i\, d\Omega$ where $i\, d\Omega$ is the illumination due to a small pencil of rays of solid angle $d\Omega$ on a small area normal to the axis of the pencil. As before $I = I_s + I_d + I_r$, where I_s is the illumination from the angle comprising the sun's disc, $I_d = \int_0^{2\pi} i\, d\Omega$ is that due to the sky and I_r is the same integral over the lower hemisphere.

It is convenient to assume that both the sky and the lower hemisphere are uniformly bright all over. This is usually near enough to the truth for practical purposes, and implies *inter alia* that H_d and H_r are independent of the azimuth of the receiving surface.

The following relations hold, where α is the altitude of the sun, and H_s is the illumination on a vertical surface set in azimuth normal to the sun's rays:- (1) $I_s = V_s \operatorname{cosec} \alpha = H_s \sec \alpha$; (2) $I_d = 2\, V_d = 4\, H_d$ and (3) $I_r = 2\, V_r = 4\, H_r$.

When a photo-sensitive liquid is exposed to light in a transparent tube, whose length, L, is great compared with its diameter, D, if the liquid absorbs strongly it may be considered as a cylindrical surface, instead of a plane surface as used in the photo-electric photometers. The illumination measured is then the mean for all directions normal to the axis of the cylinder, instead of that perpendicular to a plane. This must be remembered when comparing the results obtained with the two types of photometer, viz. the Uranyl oxalate and methylene blue tubes compared with the photo-electric photometer.

Thus a vertically exposed tube measures the mean horizontal illumination for all azimuths, $\bar{H}$, the total light flux received being $\pi L D (H_d + H_r) + L D H_s$, or $\pi L D \bar{H}$, where $\bar{H} = H_d + H_r + \frac{H_s}{\pi}$. It is obvious that, when α is large, direct sunlight

does not contribute very much to $\bar{H}$, as H_s (i.e. $I_s \cos\alpha$) is small. This must be remembered when interpreting results obtained in different latitudes.

In the absence of sunlight the orientation of an exposed tube is immaterial, so that the rate of reaction corresponds to a light flux π L D $(H_d + H_r)$ i.e. π L D $\left(\frac{V_d + V_r}{2}\right)$. In direct sunlight the light flux will be increased by L D V_s (i.e. L D $I_s \sin\alpha$) when the exis of the tube is in the sun's azimuth, and by L D I_s when it is perpendicular to it. Thus we find that the mean vertical illumination recorded by the tube varies, according to its azimuth, from $\frac{V_d + V_r}{2} + \frac{V_s}{\pi}$ to $\frac{V_d + V_r}{2} + \frac{I_s}{\pi}$

When a tube is standardised against a lamp, as are Hill's methylene blue tubes, the effective area of the tube is only L D, whereas when used to measure $\bar{H}$ its effective area is π L D. A tube standardised against a lamp therefore measures $\pi(H_d + H_r)$ i.e. $\pi(I_d + I_r)$, as far as diffuse skylight and reflected light are concerned; for pure sunlight it measures H_s, (i.e. $I_s \cos\alpha$), or I_s, according as the tubes are exposed vertically or normal to the sun's rays. Thus the fact that diffuse skylight produced more action, as found by Hill (1927), on such tubes than did the direct sunlight does not necessarily mean that the same would be true for a plane surface.

The measurement of I is probably the best way of recording the photosynthetic activity of the light for a unicellular alga, and was for that reason adopted in our 1925 paper. It requires, however, a knowledge of the angular distribution of the light. In all our later work we record what is actually measured, V, or sometimes M, since the latter accords better with the distribution of plants in the purliens of a wood.

Corrections must be introduced for reflection losses at the photometer windows, the value of this factor for pure sunlight only becomes 1.01 when $\alpha = 50^\circ$, 1.02 at 40°, 1.06 at 30°, 1.16 at 20°. For uniformly diffused skylight it is 1.06. Values of "f" and $\operatorname{cosec}\alpha = \frac{I}{V}$ have been tabulated (1926, 1, p.184 and 2, p.280).

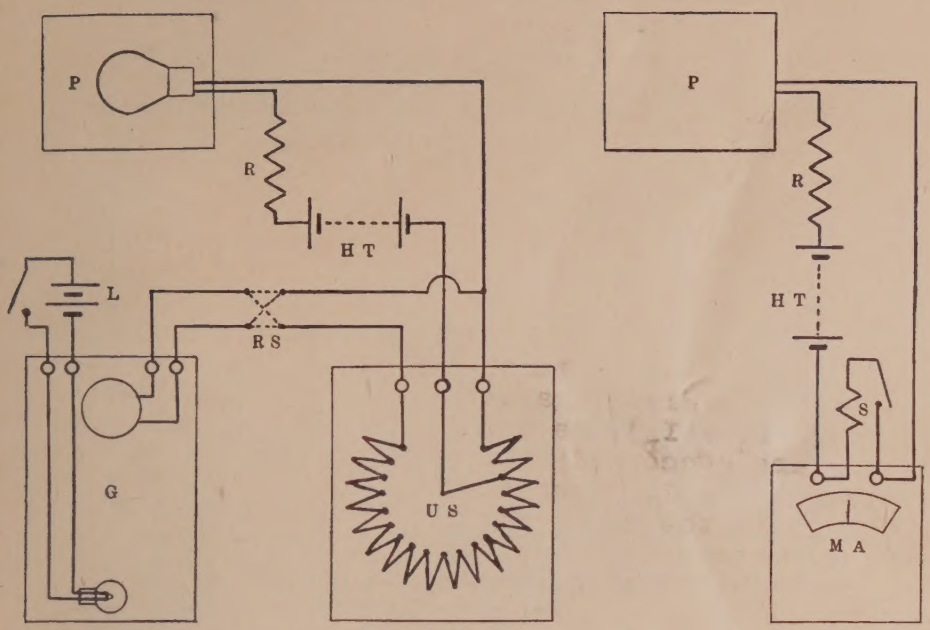


FIG. 1.

Arrangement of photometers and galvanometers at shaded base, left, and open base, right. L, galvanometer lamp battery. G, portable mirror galvanometer. RS, reversing switch. US, universal shunt. HT, high tension batteries, 60 volts. R, safety resistances, 10,000 ohms. P, photometers, the photo-electric cell is indicated in that on the left. MA, Onwood micro-ammeter. S, shunt, to one-fifth. For standardization of G, the P circuit was removed, and MA, with dry cell, connected to US instead. For comparison of the three photometers they were connected, in quick succession, to US, but only one is shown in figure.

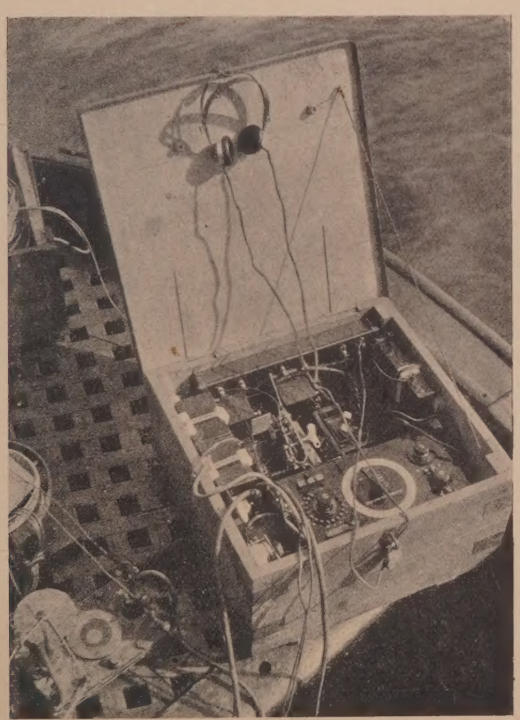
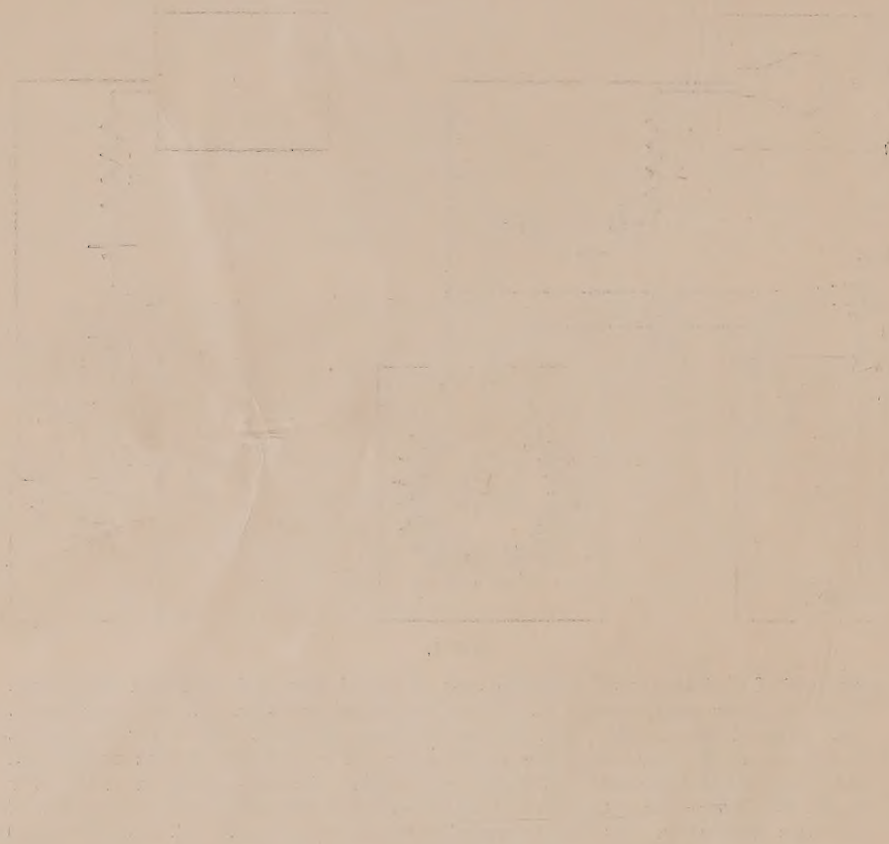


PLATE A



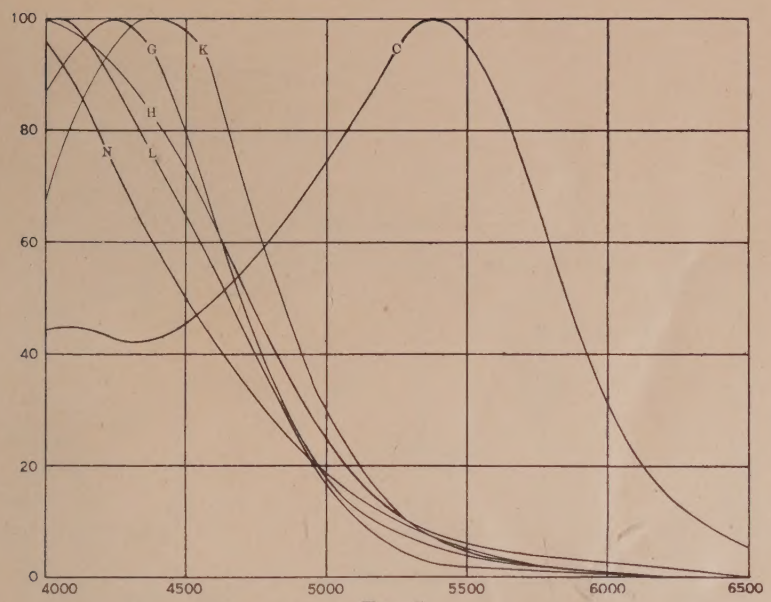


FIG. 5.

The ordinates show the percentage sensitivity of the photometers for various wave lengths as plotted in Ångstrom units on the abscissæ. The photometers contain photo-electric cells as follows:—C, a gas-filled cæsium cell; K, a gas-filled potassium-hydride cell; G, H, and L, vacuum potassium cells; N, a vacuum sodium cell.

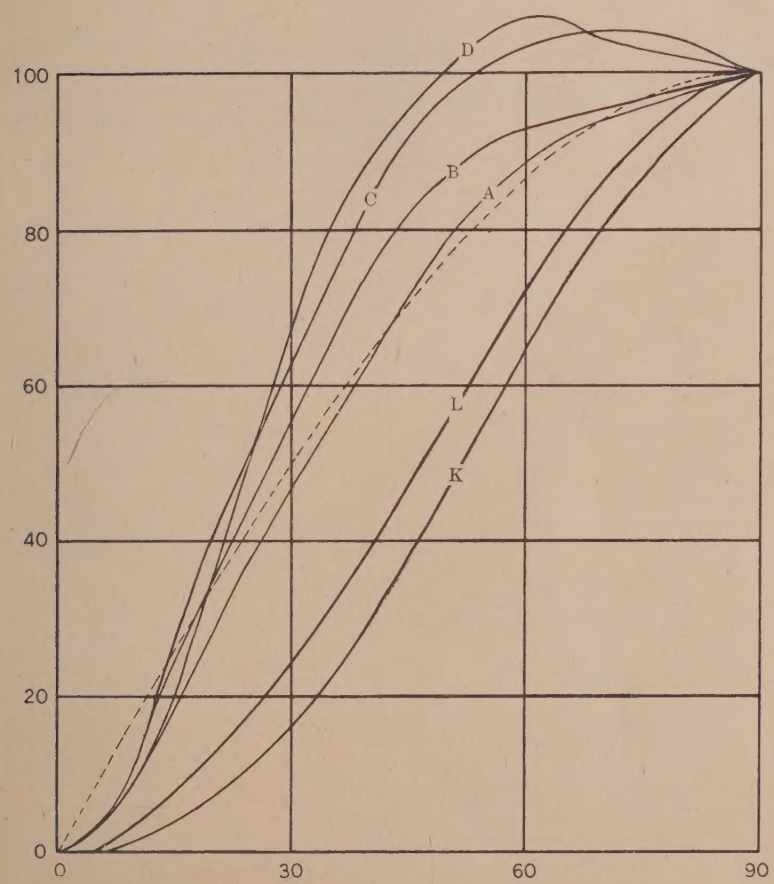


FIG. 6.

The ordinates are percentage sensitivities of the photometers and the abscissæ the altitude of the light source in degrees. Curves A, B, C, and D show the relative effects of a beam of parallel light of variable altitude for four rectangular azimuths on photometer G. Curves K and L show the mean effects for each of the four azimuths for these photometers. The differences between the various azimuths were very much smaller than with G, probably because the windows in the diffusing ground glass were narrower. The dotted sine curve shows what the effect would be with a perfect diffusing surface and no reflection losses at the front surface of the window.

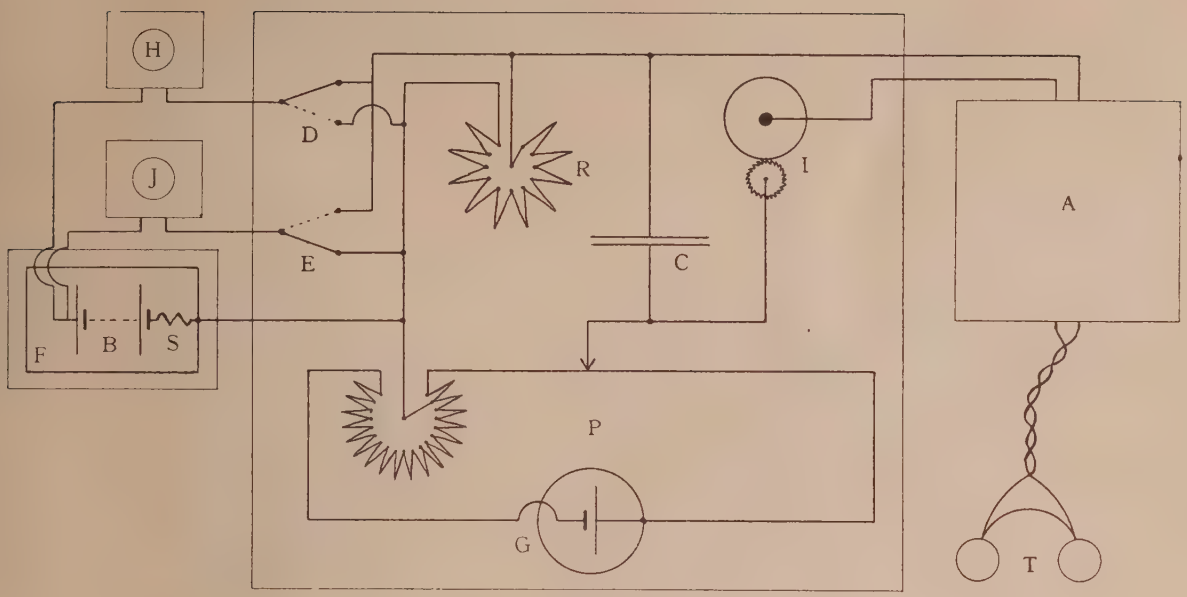


FIG. 2.

A, amplifier; B, high tension batteries; C, condenser; D and E, switches; F, metal box, insulated from outer wooden one; G, guard plate, on which stands potentiometer accumulator; H, vacuum photo-electric cell in deck photometer; J, gas-filled photo-electric cell in submarine photometer; I, interrupter; P, potentiometer; R, 100,000 ohm resistance, sub-divided; S, 10,000 ohm safety resistance; T, telephone.

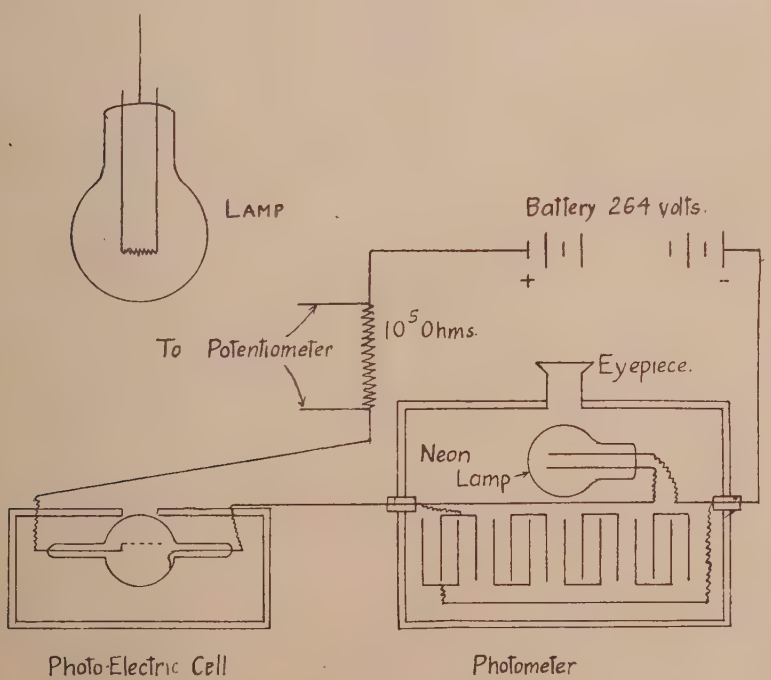


FIG. 3.

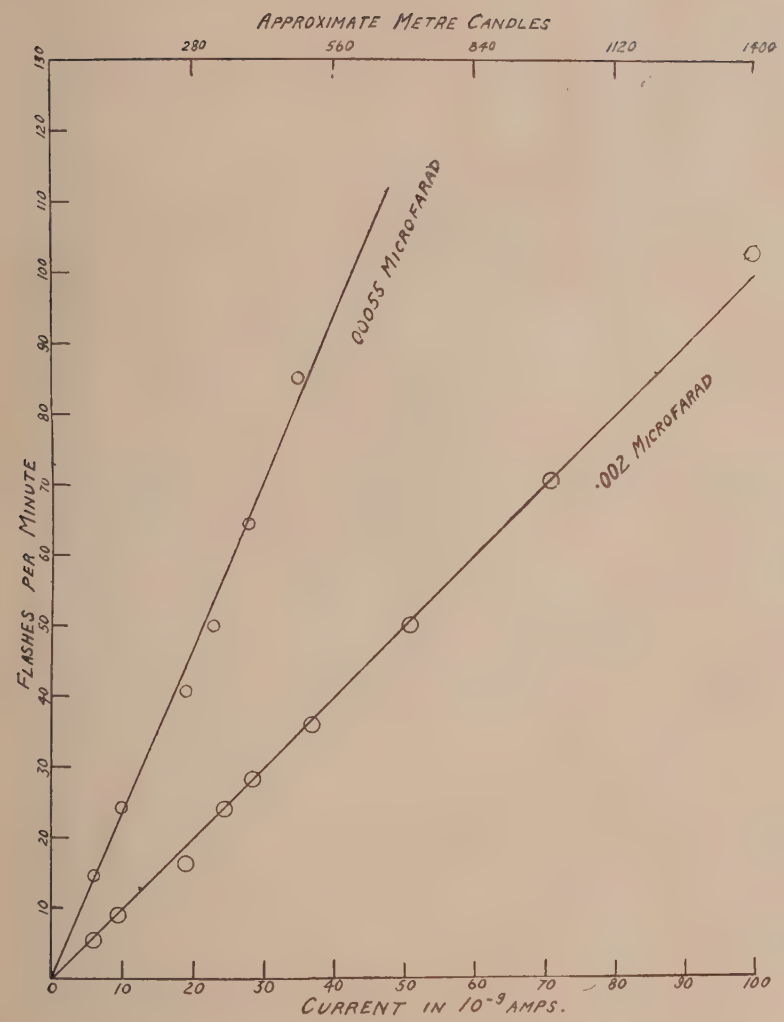

APPROXIMATE METRE CANDLES
280
560
840
1120
1400
FLASHES PER MINUTE
0
10
20
30
40
50
60
70
80
90
100
110
120
130
.0055 MICROFARAD
.002 MICROFARAD
0
10
20
30
40
50
60
70
80
90
100
CURRENT IN 10^{-9} AMPS.

FIG. 4.

MEASUREMENT OF THE PHOTO-ELECTRIC CURRENT.

1. Galvanometer Methods. The current may be measured by a galvanometer, a portable instrument being required for work out of doors. For this purpose we have used a Tinsley portable galvanometer and an Onwood microammeter (Gambrell) with suitable shunts as shown in Fig.1.

2. Potentiometer Null Point Method for use on a ship. For work at sea we have used a potentiometer method (Poole 1925). In it the current is measured by noting the drop in potential across 100,000 ohms using a telephone as a null point indicator. An interrupter, made from a "Meccano" motor with slowing vanes, is included in the telephone circuit, which is shunted by a condenser, and the sensitivity is increased by the use of a two valve amplifier. Plate A shows the general arrangement of the apparatus, the amplifier being attached to the back wall of the box, with high tension batteries on the side walls. The interrupter is visible in the middle, next the potentiometer, which is in front. In the left hand lower corner is shown a gun-metal submarine photometer, and next to it one half of a deck photometer, mounted in gimbals, appears.

This arrangement was subsequently modified to secure better insulation in damp weather. Fig.2 shows the present form.

The potentiometer being divided to 0.1 millivolt and the resistance being 100,000 W. the current measured is 10^{-9} amp. per scale division. Under the best conditions readings may be made to 0.5 scale division.

3. Integration over a short period with the neon lamp. The neon lamp photometer, introduced by J.H.J.Poole (1928) offers a method of measuring illumination which is sensitive, reasonably portable, robust, comparatively cheap and has the great advantage that it integrates the illumination over the time of measurement, so that it should prove specially suitable for determining average values in sites subject to rapid fluctuations, such as just below the surface of the sea and in shallow water in rapid motion, or in a woodland site where swaying branches cut off sunlight intermittently.

If a small current, such as is obtained from a high tension battery through a very high resistance or a photo-electric cell, charges up a condenser across the terminals of which a neon lamp is connected, the latter partially discharges the condenser at intervals, the discharges being rendered visible by flashes which occur at a rate which is a function of the charging current. Fig.3 shows diagrammatically the arrangement used by Poole to ascertain the nature of this function, and Fig.4 makes it clear that for each value of the capacity the relation between the rate of flashing, as measured with a stop-watch, and the current is a linear one.

The apparatus has since been improved by the addition of a system of guard rings and the use of a special type of neon lamp which by eliminating the effect of surface leaks, render the rate of flashing proportional to the current.

Accordingly a calibration of the apparatus, for each condenser, in terms of current or with a particular photo-electric cell in metre candles, enables one to determine the illumination by timing the rate of flashing. Using a vacuum sodium cell of the Burt type illuminations of less than one metre candle could be measured with a shunting capacity 0.0005 micro farad; by increasing the latter up to 0.5 u. F. the illumination, V, of full daylight could be measured. It is

necessary to pay careful attention to the insulation of the neon lamp and condensers, of which a series (Dubilier type) are mounted in a box with the lamp. The only heavy and bulky part of the apparatus is the box of high tension dry batteries to give about 240 volts.

The flashing of the lamp may be demonstrated to an audience by the inclusion in the circuit of a two or three stage low-frequency amplifier and a loud speaker, when each flash is reproduced as a rap.

4. Integration over longer periods by photo-electrolysis. For integration over longer periods use may be made of the method of photo-electrolysis (1929, 1). With a sensitive vacuum sodium photo-electric cell of the Burt type a very dilute solution of sodium bicarbonate may be electrolysed, the production of alkali being observed by the formation of a blue sheath round the kathode. On a bright afternoon in November this was noted within ten seconds after making the connection. With an illumination of 20,000 metre candles the photometer used, at 60 volts anode potential would give 23 micro amperes. This gives 55×10^{-6} mg. of sodium, or 2.4×10^{-6} mg. of hydrogen for the visible effect noted above in 10 seconds. Assuming the volume of the layer in which the blue colour was produced to be 0.1 c.c., in pure water the colour change would involve a diminution in hydrogen ion content of 0.0095×10^{-6} mg., which is about 250 times less than the change involved in the experiment. Thus, by boiling out most of the carbon dioxide, and adding an even more minute amount of bicarbonate than was actually used, it would be possible considerably to increase the sensitiveness of the reaction. The method can be made quantitative with suitable precautions, but for use over periods of a day or more the photo-electric deposition of copper is preferable. It is advisable to use a copper anode as the solution does not then become more acid, since the acid liberated attacks the anode instead of redissolving some of the metal deposited on the kathode. About 0.13 mg. of copper is deposited on a winter day, taking this as 10,000 m.c. for 10 hours. A summer day averaging 50,000 m.c. for 14 hours would deposit 0.92 mg. with the same sensitive cell. The estimation of the copper was carried out by the potassium ethyl xanthate method of Scott and Derby (1922).

5. Continuous measurement by means of a recording galvanometer. It is obvious that the daily variations in illumination may also be followed, and the total quantity integrated, by recording the galvanometer deflections of method (1) on photographic paper on a revolving drum. For this purpose one of the standard 12 hour drums is being modified, as, oddly enough, 24 hour drums do not appear to be stocked.

In measurements of this sort, as in routine photo-electrolysis, attention has to be paid to the absence of weathering of the exposed glass surface of the photometer and to the constancy of the anode potential, as a source of which the use of storage batteries is to be preferred to the usual 60 volt dry battery.

PHOTO-ELECTRIC CELLS.

a. Types of cell, colour sensitivity and use of light filters. A typical photo-electric cell consists of an evacuated bulb inside which has been deposited a film of an alkali metal, a window free from deposit having been left for the entrance of light. The film constitutes the kathode, the anode being a wire ring or grid placed between the window and the coated surface opposite it. A guard ring lead is attached near the anode, but is only required as a rule for measurements of great sensitivity. The highly evacuated type of cell is stable and shows neither time lag nor fatigue. It is said to be permanent even over long periods and our experience confirms this. This type of cell was introduced by the General Electric Co. (1924). Those prepared by R.C.Burt are of necessity limited to sodium only, since the metal is deposited by electrolysis of the glass. These cells are of large size, like an electric light bulb, and are mounted on a radio-valve socket.

Highly sensitive cells filled with helium, argon, or neon under suitable low pressures have been in use for many years The sensitivity may be still further increased by the formation of a colloidal hydride of the metal by making it the kathode in a glow discharge through hydrogen at a low pressure. The hydrogen remaining is removed and replaced by an inert gas. Our experience with such cells has been that they lack the constancy of the vacuum type, and their use should be avoided whenever sufficient sensitivity can otherwise be obtained. The large Burt cells are very well suited for portable apparatus. Reference may be made to Allen's Photo-electricity (1925) for a general account of all types known up to that date.

The manner in which photo-electric activity varies with wave-length is somewhat complicated, and for a discussion of the factors concerned reference may be made to Allen. Even with the same alkali metal small variations are experienced from cell to cell. The colour sensitivities of various cells used by us are shown in Fig.5. These were determined by measuring the energy in a spectrum band with a Moll vacuum thermopile and a very sensitive Kipp type Z galvanometer, the latter being also used to measure the photo-electric current. The ratio of the photo-electric to the thermo-electric current, for any given lamp setting, was taken as the relative sensitivity of the cell for light of wave length corresponding to the centre of the spectrum band used (1928) These determinations were made with diffusing windows of ground glass in the various photometers. Since then a much better diffusing surface, glass opal-flashed on both surfaces, has been substituted. The importance of this may be recognized by inspection of Fig.6. With the double surface flashed opal glass (J.Hetley & Co.) the theoretical sine curve, shown dotted in the figure, was obtained. This glass is, moreover, approximately non-selective in its action on light of various wave lengths in the visible range.

The ultra-violet range is, however, heavily cut out by this glass. The effect is to render the sodium and potassium photo-electric cells very similar in their response to the ultra violet when thus mounted, even though the Burt sodium cell is stated to have a maximum sensitivity at about 3,600 Å.U Unscreened, it measures the ultra-violet well, with clear sun and blue sky it gives 14% of its total unscreened reading when screened with a red purple Corex A filter, 10.2 mm. thick, which reduces the visible almost to nil and transmits about 42% at 3,400 Å.U. and 14% at 3,000 Å.U.

b. Standardization of photo-electric photometers. An open carbon arc lamp was used (1925, 1928). In the more recent work use was

made of the results of Forrest (1913) and N.A.Allen (1921). The former has shown that the luminosity perpendicular to the face of the positive carbon is about 173 candle-power per sq. mm., and the latter found that under the conditions of his work the current was 0.746 ampere per sq. mm Combining these two we get 232 c.p. per ampere in a direction perpendicular to the face of the positive carbon. Using such a light source it was found that with photometer H, which contains a G.E.C. vacuum potassium cell, 40 metre candles gives 10^{-9} ampere with anode potential 60 volts. This cell is about four times as sensitive as a similar cell, G, which we used for several years for the calibration of a gas-filled potassium hydride cell of the Kunz type. With 3 volts anode potential the latter was about twice as sensitive as C, increasing to 35 times with 120 volts. Another potassium-hydride argon filled cell made by the General Electric Co (photometer J) was found to be 66 times as sensitive as H, viz about 264 times as sensitive as C, with anode potential 88 volts. By raising the latter so as to produce a glow discharge, and then working with anode potential somewhat below that necessary to produce the discharge with the illumination to be measured, both sensitiveness and constancy are greatly improved.

The Burt vacuum cells have been found to be from 19.4 to 50.3 times as sensitive as H.

c. Constancy of cells. In order to satisfy ourselves as to the constancy of the vacuum photometers a test-lantern was constructed (1928).

It consists of a large white enamelled iron tumbler through the bottom of which a circular hole was bored to take a lamp-holder with a 6-volt, 18-watt vacuum lamp. The lantern was standardised at 5.50 volts for each photometer shortly after the latter had been standardised with the arc, and the illumination in metre candles recorded. As this lamp is only used occasionally for a few minutes, and at a reduced voltage, its candle power should remain approximately constant for years. No change has been detected in the photometers by its use, or by cross-checking them.

METHOD OF TAKING OBSERVATIONS.

When measuring the illumination in the open it is necessary to select a site as nearly as possible free from all obstruction to light even of low angle. When at sea the stand, containing the gimbals on which the photometer rested, was lashed in position on the roof of the deck house of the Marine Biological Association's steam drifter-trawler "Salpa", the stern of which was kept pointing towards the sun. This site afforded a very good view of the whole sky. On shore, positions such as the front parapet of the M.B.A. Laboratory roof, at Plymouth, an open position near the edge of the cliff at Cawsand, or the top of a garden wall on a hill at Antony were used. With the submarine apparatus, used at sea and in Cawsand wood (1926) both photometers are attached to one measuring instrument. This plan was also adopted at Antony in 1927 using a portable galvanometer, but in 1928 the use of cumbersome cable lengths was avoided by having the photometer in the open site connected to a microammeter which was read at definite times by one observer, while another, using a portable galvanometer or a microammeter with a more open scale, made the observations in selected shaded sites, noting the time of each.

RATIO OF TOTAL VERTICAL TO VERTICAL DIFFUSE LIGHT.

By shading the photometer window by the interposition of a small object held at some distance it is possible to cut off the direct rays of the sun without at the same time diminishing appreciably the light received from the blue sky or reflected from cloud masses. According to Aldrich (1922) the reflecting power of clouds is 78% ± 1.1%, the value being independent of the zenith distance of the sun but it seems likely it may vary with the type of cloud over a wide range. This ratio of the total to the diffuse vertical illumination may be denoted by β. Numerous measurements have been made using photometers G or H, both vacuum potassium cells. It was, therefore, of importance to ascertain whether, on changing over to the Burt type of cell for use with a microammeter, any serious difference was introduced in the value of β. With diffuse light from a grey sky the sensitivity of B 223 to H was found to be 50.3 on Sept. 27th, 1928; on June 21st, 1929, with clear sun and blue sky, consecutive observations gave 51.8 for the same ratio, which appears to indicate that no appreciable changes had occurred in either cell and that their ratio determined in white light from a grey sky and in a mixture of sunlight and skylight was closely the same, the sodium cell being perhaps slightly more sensitive to skylight. Thus on June 21st observations made in quick succession between 11·11 and 11·15 G.M.T. gave, with H, β = 3.62, β = 3.40, and with B 223 β = 3.30 and 3.21; the last value was obtained just before a cloud obscured the sun; at 11·17 the value was β = 3.32. On June 26th at 12·8 G.M.T., with B 223, β = 3.52; at 12·9, β = 3.44 with H, and at 12·11, β = 3.47 with B223.

In general it may be said that β = 1.5 indicates weak "watery" sunlight, β = 2 may indicate sunlight at 3 - 4 p.m. in April with blue sky and heavy clouds or a hazy midday sky early in May with a few light clouds or similar conditions in October. Values such as β 3 or 3.5 are found with light blue summer skies and a certain amount of diffuse light from clouds. Values such as β = 4 or over have been observed only when the vertical illumination exceeds 100,000 m.c. On one occasion with bright sun, clear blue sky, and no clouds a value as high

as 6 was found for β, as mentioned further on. The suspicion that too much skylight was cut off lurks in our minds, though it must be said that the pure sunlight, which is got by difference, was about what one would expect, instead of being much too high.

THE DAYLIGHT FACTOR, AND ITS DEGREE OF CONSTANCY; WOODLAND ILLUMINATION.

The best way of expressing the illumination in a wood, or shaded site, is, from the ecological standpoint, to use the daylight factor $\delta = \frac{V_w}{V_d}$, where V_w is the vertical illumination in the wood and V_d that in the open, neither receiving direct sunlight, and the illumination being taken as uniform over the whole sky. In practice the sky is rarely uniform, even in the absence of direct sunlight, so δ may be expected to vary somewhat. It is none the less, especially if averaged over a day, the best indication of the ecological lighting conditions, except at the edge of a wood, where the distribution of the vegetation is more in agreement with $\delta_m = \frac{M_{wm}}{V_d}$.

TABLE 1.

Variations in δ. $\beta = 1.92$ at 1·15 p.m., Oct. 13th, 1928, after that $\beta = 1.0$ $\delta = \frac{V_w}{V}\beta$.

G.M.T.	δ	Notes	G.M.T.	δ	Notes
p.m.			p.m.		
1·15	59.8	Sun out, B 1.92	2·26	66.2	Bright clouds in region of sun.
2·19	56.0	Uniformly overcast	2·34	63.7	Disc not visible.
2·20	57.0				
2·21	61.4				By uranyl oxalate, May 30th.
			a.m.		
2·22	61.4	Sky clearing at zenith.	5·40-8·40	57.8	Overcast morning.
2·24	61.4		8·40-11·40	61.4	Murky, then rain and clearing up. Sun obscured throughout.
2·25	67.7	Zenithal blue patches.			

Table 1 shows the variation found in δ on a garden lawn shaded to the south by trees and the north-west by a three-storey house.

If, however, it is desired to determine δ when the sun is shining use must be made of the factor β to correct the value of V and bring it to V_d, because the diffuse light in the wood is due to illumination coming from innumerable shafts of skylight, provided of course that no direct sunlight falls on the position of the photometer, then $\delta = \frac{V_w}{V_d} = \frac{V_w}{V}\beta$. Reasons based upon the

percentage of the possible sunshine received during the six leafy months have been adduced (1926) to show that δ is also a good index of the general lighting conditions of a spot which receives direct sunlight for a portion of the day. Suppose a site has a daylight factor 75 per cent and goes into shade at noon β being 3 in the open, viz. total light 3, diffuse light 1, sunlight 2. The site will, therefore, receive up to noon a total illumination $2 + \frac{3}{4}$ and for it $\beta = \frac{2.75}{0.75} = 3.7$ (nearly). After noon the illumination will be $\frac{3}{4}$; so for the whole day the site will score 3.5 out of a possible 6, assuming continuous sunshine, also that $\beta = 3$ throughout, which is an over-estimate. On this hypothesis the site may be rated as receiving 58 per cent of the possible. Since for England, S.W., the average number of hours of sunshine is 36 per cent of the possible from May - October, the values may be weighted, and the site rated approximately as $\frac{58 \times 1 + 75 \times 2}{3} = 70$ per cent almost, which is not very far from δ - 75, especially since 58 per cent is too low a value for the forenoon because β is below 3 for early morning and late afternoon sun. With a site facing north, for which δ = 50%, the use of the factor alone might be rather misleading, so the aspect should be stated.

ILLUMINATION IN SHADED SITES.

It has been shown (1926;) that in a mixed deciduous wood in early autumn δ may be as low as 1 - 2 per cent, which, it may be added, is about the value found at 20 - 30 metres in clear water off the coast of Cornwall, though the degree of clearness varies greatly. The floor of such a wood is devoid of grass, and is mainly covered with straggling Hedera helix, with perhaps a little Lonicera periclymenum and Rubus fruticosus, stunted and straggling on the ground with values δ 2.9 to 0.8, but more or less thriving with values from δ 56 - 16, and rather less than more with δ 4.3. Table 2 illustrates the method of studying such situations. The measurements were made with the submarine outfit, but the portable apparatus is now available (1929, 2 and 4).

The sites examined in Cawsand wood were as follows:-

Site A.- On path just below bank to east of wood, receives full sunlight up to about 11 a.m., but is shaded by wood. Mixed grasses and Rubus fruticosus flourish and received 61 - 52 per cent of total daylight when examined, including some sunlight.

Site B.- Under first tree Fagus sylvatica at edge of wood, a good N.E. aspect, Quercusrobur scrub, Acer pseudo-platanus, young, Castanea vulgaris, young, Pteris aquilina, R. fruticosus, Rosa arvensis, Bromus asper, a little H. helix, Geranium robertianum, Lonicera periclymenum; and, a little nearer the light, Tamus communis twining on P. aquilina; Scilla nutans frequent in spring; dry soil, pH6.2, δ -18. About a metre nearer the light Eupatorium cannabinum, Galium mollugo, and Dactylis glomerata occurred. These three may require more light than δ = 18, E. cannabinum previously found at δ = 34 and G. mollugo at δ = 16.5.

Site C.- Under second tree (F. sylvatica) in wood, 10 m. further in, much H. helix straggling on ground, also L. periclymenum and stunted straggling R. fruticosus, some P. aquilina, Fraxinus excelsior, young, Castanea vulgaris, young, A. pseudo-platanus,

young, Q. robur, young, Rosa arvensis, Rubia peregrina, Lysimachia nemorum, no grass; S. nutans frequent in spring; dry soil, pH5.7; δ = 2.9

Site D.- About 11 m. further in under young F. sylvatica, overarched by other trees, H. helix straggling, dominant, a little stunted R. fruticosus and L. periclymenum straggling, one plant Primula veris, dry soil, pH5.8; δ = 1.8. S. nutans frequent in spring, Mercurialis perennis absent.

TABLE 2.

Sept. 10, 1925. Area No.2. Base in open, near edge of cliff, 20 metres east of Cawsand wood. All values of β refer to base. Photometers horizontal. Wind N.W.

Site	Weather conditions.	G.M.T.	β	Illumination, metre candles. In open. V	In wood V_w	Percentages $\frac{V_w}{V}$	$\delta = \frac{V_w \beta}{V}$	pH
A	Sun through light clouds	11·13	-	33,800	20,600	61*	-	-
"	Sun out, clear sky	11·19	-	74,700	38,900	52*	-	-
-	Do.	11·53	3.1	-	-	-	-	-
B	Sun out, light fleecy clouds.	11·55	-	81,500	4,770	5.8	18.1 +	6.2
"	Clouds over sun.	11·59	1.0	25,400	4,630	18.3	18.3 ‡	6.2
"	Sun out, blue sky, light clouds.	12 · 2	-	76,700	5,310	6.9	20.7 ‡	6.2
-	11·55 obs. with 11·59	-	3.2	-	-	-	-	-
-	11·59 obs. with 12 · 2	-	3.0	-	-	-	-	-
C	Cloud over sun	12·42	1.0	25,400	730	2.9	2.9	5.7
"	Sun through light clouds	12·45	-	54,100	830	1.5	3.1 ¤	5.7
-	12·42 obs. with 12·45	-	2.1	-	-	-	-	-
D	Cloud over sun, position of open base now shaded by wood when sun is out.	2 · 5	1.0	34,400	620	1.8	1.8	5.8

* Received sunlight through topmost branches of wood.
+ From β = 3.1. ‡ From β = 3.0. ¤ From β = 2.1.

As well as an alteration in intensity there is, in a wood, an alteration in the spectral energy distribution. Klugh (1925) has discussed this; it has previously received attention from Zederbauer (1907) and the Burns (1923,1927). By his photographic method Klugh showed that in dense spruce woods at St. Andrews, New Brunswick, on Sept. 8th, 1924, with bright sun and a clear sky, the red, λ5900 A.V. and over, was 0.005 per cent of the external red; the green, λ4900-5900 approx., 0.05 per cent. and the blue, λ4000-5000 approx., 0.12 per cent. It seems obvious from these results that almost the whole of the light must have passed through plant tissues or been reflected by them. Our apparatus measures mainly the blue. The sites we examined being more open than the above, quoted from Klugh, the changes in spectral character were, as it were, diluted by direct skylight. It is our intention to pay further attention to such alterations in the colour of the light in shaded sites.

SEASONAL CHANGES IN ILLUMINATION.

No time has as yet been available for making a regular series of observations, but Table 3 shows those made in the course of various researches. The maximum values for the vertical illumination vary from 134 to 11.0 thousand metre candles. Paterson and Walsh (1915) give values obtained in Apl.-June and Sept.-Dec. 1914 for the diffused light on a white card shielded from direct sunlight by means of an illuminometer.

The maximum value was 58,430 m.c. in June, for which month the mean was also a maximum, 44,130. Our maximum value for V_d is 69,500, for June 13,1928, followed by 54,200 for Sept.1, 1925 and 48,900 for Sept.5, 1927 - all three on days with sun totally obscured. With $\beta = 2$ on May 5, 1928, $V_d = 43,200$, which was just surpassed with $\beta = 3$ on July 11, 1928 when V_d 43,500 with $V = 130,500$. With the maximum value found, $V = 134,000$, and $\beta = 4$, $V_d = 33,500$. Our table has twelve September records for V_d, which average 32,000, which is in good accord with 32,600 the value found by Paterson and Walsh. The important point is not the fortuitous closeness of the figures but the fact that the two totally different methods are in tolerably good agreement. A direct comparison is to be desired.

TABLE 3.

Showing the maximum values of the vertical illumination in thousands of metre candles, recorded by a potassium or sodium photo-electric cell (standardised by means of a carbon arc) in open situations during the mid-day hours. β when determined on roof of deck house, at sea, is given to nearest 0.5, but when determined on shore is given to two places of decimals, with an error in the second, probably less than 0.05.

Date	β	V	V_d	Date	β	V	V_d
2/1/29	1.0	15.2	15.2	10/9/25	3.1	81.5	26.2
1/3/28	4.0	66.5	16.6	12/9/27	1.5	65.2	43.5
6/3/28	3.0	75.0	25.0	18/9/28	2.5	78.5	31.4
27/3/28	1.5	66.5	44.3	23/9/25	2.8	58.9	21.0
5/4/28	2.5	86.0	34.4	1/10/25	1.5	24.5	16.3
19/4/28	4.0	134.0	33.5	2/10/28	2.5	65.5	26.2
7/5/28	2.0	86.5	43.2	3/10/27	4.0	73.3	18.3
13/6/28	1.0	69.5	69.5	5/10/27	4.0	70.0	17.5
19/6/29	3.34	103.7	31.1	6/10/27	2.0	45.3	22.6
20/6/29	1.00	30.6	30.6	12/10/28	2.0	62.0	31.0
21/6/29	4.28	109.0	25.5	13/10/28	1.92	54.5	28.4
26/6/29	3.47	103.0	29.7	2/11/28	2.19	46.9	21.4
4/7/28	6.0	126.0	21.0	3/11/28	1.00	17.0	17.0
11/7/28	3.0	130.5	43.5	9/11/28	1.61	35.9	22.3
23/7/28	4.5	121.5	27.0	30/11/28	1.0	15.3	15.3
9/8/28	1.5	56.0	37.3	14/12/27	1.5	30.8	20.5
29/8/28	4.0	111.5	27.9	17/12/27	1.0	13.0	13.0
1/9/25	1.0	54.2	54.2	19/12/27	1.0	12.5	12.5
2/9/25	3.5	84.4	24.1	20/12/27	1.0	11.1	11.1
2/9/27	4.0	109.5	27.4	21/12/27	1.7	33.5	19.7
3/9/25	3.0	74.0	24.7	22/12/27	1.0	11.0	11.0
5/9/27	1.0	48.9	48.9				
7/9/25	3.1	73.6	23.7				
7/9/27	4.0	100.0	25.0				
9/9/27	1.0	33.9	33.9				

SUBMARINE ILLUMINATION.

Shalford and Gail (1922) introduced the photo-electric cell for measurements of submarine illumination and spectrophotometric measurements by Knudsen were published the same year. These and earlier photographic work have been reviewed by one of us [Atkins, 1926]. We have elsewhere (1929,3) described photo-electric measurements made in the English Channel throughout the year.

The vertical absorption coefficient, U_V, measures the relative reduction of illumination per metre depth, U - the true absorption coefficient depending upon the angular distribution of the light, which travels a longer course than d, the depth. It is, for vertical illumination, defined by the well known equation $V = V_0 e^{-ud}$, whence $u_V = \frac{2.3}{d}(\log_{10} p_1 - \log_{10} p_2)$ where the illumination p is recorded as a percentage of the simultaneous value of the surface light V and d' is the difference in depth between the two points.

Observations were made at International Hydrographic Station England No.1, E 1, 22 miles S.W. of Plymouth. These may be illustrated by the records of Series 28, shown in Table 4, made on Apl. 19, 1928 when the water was exceptionally clear. The illuminations are recorded in thousands of metre candles (k.m.c.) in air V_a and in water V.

TABLE 4.

Measurements of submarine illumination.

Date, Remarks, etc.	T. G.M.T.	a	Light	β	d metres	Va k.m.c.	V k.m.c.	p %	U_v
Series 28. 19.4.28.	11.58 a.m.	51	Bright Sun	4	r	109	109	100	-
K Photometer, At El.	12.8 p.m.	"	"	4	a	114	109	95.5	-
Wind N.W., light. Slight	12.21 "	"	Light Cloud	2	5	45.5	22.7	50	0.090*
swell from N W. Clear	12.31 "	"	"	"	10	49	17.2	35.1	0.077
sky with clouds. High	12.40 "	"	Sun	3.5	"	81	26.7	33.0	0.077
water 5.23 p.m. Secchi	12.50 "	"	Bright Sun	4	"	121	41	33.8	0.077
disc 18 m. at 4.18 p.m.	12.56 "	"	"	"	15	134	29.6	22.1	0.078
	1.49 "	48	"	"	"	102	24.6	24.0	0.078
	1.54 "	47	"	"	20	100	15.6	15.6	0.079
	1.58 "	"	"	"	25	100	10.4	10.4	0.075
	2.3 "	46	"	"	30	99	7.35	7.4	0.088
	2.11 "	45	"	"	35	97	4.15	4.25	0.119
	2.23 "	43	"	"	40	94	2.12	2.25	0.121
	2.30 "	42	"	"	45	94	1.20	1.28	0.114
	2.45 "	40	"	"	50	89	0.65	0.725	0.115
	3. 0 "	38	"	"	55	84	0.342	0.405	0.109
	3.11 "	37	"	"	60	79.5	0.192	0.242	0.100
	3.15 "	36	"	"	65	78.5	0.116	0.148	0.090
	3.19 "	35	"	"	70	77.5	0.076	0.098	-
	3.35 "	34	"	3.5	45	74	0.73	0.985	-
	3.53 "	31	"	"	25	73.5	5.8	7.9	-
	3.58 "	30	Cloudy	1	"	25.3	1.77	7.0	-
	4.1 "	29	Bright Sun	3	"	69.5	5.55	8.0	-
	4.8 "	28	"	"	r	68	68	100	-

* The asterisk denotes that the surface reflection loss was taken as 15 per cent in calculating this value.

URANYL OXALATE PHOTOMETRY.

Of the various photochemical reactions known and listed by Allmand (1925) and Kistrakowsky (1928) none appears to have greater advantages on the score of reliability and ease of manipulation than the decomposition of oxalic acid in presence of a uranium salt as catalyst.

It has been studied by many workers from Niepce de Saint - Victor and Corvizart (1859) onwards, notably by Bacon (1907, 1910), Büchi (1924), and also Anderson and Robinson (1925). We have reviewed earlier work elsewhere (1929, 5), and carried out a comparison between the rate of decomposition of the oxalic acid, exposed in quartz or glass tubes, and the vertical illumination determined photo-electrically.

Use has very generally been made of the proportions of the reagents given by Anderson and Robinson, namely 0.1 N oxalic acid and approximately 0.01 M uranyl sulphate, $UO_2 SO_4 3 H_2O$, viz. 4.27 g. per litre (0.01 M = 4.203g.)

The method was proposed by them for the study of lamps, such as the quartz mercury arc. For this purpose it has been used by Gillam and Morton (1927, 1928) and by us (1929,6).

The most exhaustive measurements of daylight by this method are those of Tonney, Somers, and Marti (1928), whose procedure was to place 25 c.c. of the reaction mixture in a rectangular quartz cell 3.35 x 10 cm., 1.65 cm. in cross section, the walls were all covered with opaque paper save for an area of 10 sq. cm. on the lower part of one face through which the exposure was made. The vessel was placed so that the open face was always at right angles to the sun's rays. Exposures were usually made for one hour, the position being adjusted every 15 minutes. A large number of determinations were made from 1926 to 1928, and curves were obtained for the daily, monthly, and seasonal variations. The readings were correlated with the production of erythema on human skin, which corresponded to the destruction of between 3.52 and 3.72 mg. oxalic acid per sq. cm. during the time of exposure. The minimum time required to produce erythema was 35 minutes, and other exposures up to 60 minutes, which just produced a definite erythema, showed a destruction of oxalic acid within the limits given. In all cases the skin had been sponged with ether to remove the natural oils and the close agreement between the various subjects was probably due to this precaution. The maximum rate observed away from all smoke on the Indiana sand dunes, 30 miles from Chicago, was 7.12 mg. of oxalic acid per sq. cm. per hour. This is termed the climatic maximum. The authors consider their chemical results to be measurements of solar ultra violet light, relying on the statement of Anderson and Robinson that absorption is complete up to 3600 Å.U and partial as far as 4100 Å.U. According to Büchi, however, absorption proceeds considerably further into the visible spectrum; this is most important, as the solar spectrum energy distribution curve has a maximum about 5000 Å.U., and falls off very sharply towards the violet and ultra violet. By making identical exposures in tubes of quartz and of Monax resistance glass 0.9 - 1.1 mm. thick we found the ratio Q/M = 1.14, viz. the portion stopped by the Monax glass is only one eighth of the total yet it stops all erythema production, and cuts down the action on Hill's methylene blue tubes to under 40 per cent.

We prefer, therefore, to consider measurements of daylight carried out by uranyl oxalate as recording the blue, the violet and to a lesser extent, or not at all, the long and the short ultraviolet.

When there is a grey sky one still gets a good destruction of oxalic acid, even though examination fails to show any ultra violet above the intensity that can be detected with the Beck fluorescent ultra violet spectrometer directed towards the sun's disc, visible through cloud. With a clear sun, however, when the radiation is above a certain intensity the ultra violet begins to be effective and joins in the destruction of the oxalic acid We have also used this method for determining the daylight factor of shaded sites for ecological purposes (1929, 4&5). For convenience in transport, and to lessen cost, quartz tubes were used, even though the optical considerations are thereby rendered less simple than when a plane surface is exposed, as has been pointed out in an earlier section. The tubes were 13 x 1.6 cm., internal diameter 1.3 cm. For general ecological purposes they may be replaced by similar ones of Monax glass The quartz was used at first because of the mistaken idea that the glass was insufficiently transparent. Determinations were made using 10 c.c. of the reagent, and the tubes were exposed either on shore at 15° to the horizontal or at sea swinging about a mean vertical position, to measure the horizontal light. They were also used to measure the submarine illumination, for which purpose they are less satisfactory than the photo-electric cell.

After introducing suitable corrections for the difference between the light received by the tubes and by the photo-electric photometer used for standardising it was found that the N/10 oxalic acid solution was decomposed at the rate of 0.20 - 0.25 c.c. or 1 26 - 1 57 per hour per thousand metre candles; the illuminations were measured by a potassium photo-electric cell, exposed beside the tubes on the laboratory roof, the latter being at 15° to the horizontal - for which a correction was introduced. The greatest value of the ratio was with afternoon sunlight, the least with a high noon sun, intermediate values being obtained with a grey sky.

In future we hope to make measurements of total intensity, I, exposing the solution in a spherical flask as suggested in the section on "Optical Considerations".

Ultra violet photometry by an acetone solution of methylene blue.

This method though not capable of such accurate comparison, is a much better indication of the intensity of the middle (physiologically active) ultra violet than is the uranyl oxalate photometer since various glass tubes, superposed on the quartz, cut down the reaction to less than forty per cent according to our measurements, whereas the uranyl oxalate reaction, in a glass tube, proceeds at seven eighths of its rate in quartz. For details Hill's (1927) paper is readily accessible for consultation Attention should, however, be paid to the optical considerations as pointed out in an earlier section. Moreover, when the reaction has proceeded so that it corresponds to anything below 7, viz. three units of bleaching (its colour scale being 10 to 3) it is reversible, and recovers to a value close to 7 on standing overnight in the dark. Furthermore, with a tube laid horizontally, the apical end remote from the air bleaches more rapidly than does the general body of the tube beyond the middle point.

In conclusion we wish to record our indebtedness to the Royal Dublin Society and to the Marine Biological Association of the United Kingdom for the loan of blocks and for permission to make use of material from their publications.

BIBLIOGRAPHY

ABBOT, C.G., FOWLE, F.E., and ALDRICH, L.B. 1922. The sun's energy-spectrum and temperature. Ann Astrophys. Obs., Smithsonian Inst., 4, 203.

ALDRICH, L.B. 1922. The reflecting power of clouds Loc cit., 4, 375.

ALLEN, H.S. 1925. Photo-electricity. London.

ALLEN, N.A. 1921. The current density in the crater of the carbon arc Proc. Phys. Soc. (London), 33, Pt.2, 62-69.

ALLMAND, A.J. 1925. Einstein's law of photochemical equivalence. Trans. Faraday Soc., 21, 438-452.

ANDERSON, Wm T.Jr., and ROBINSON, F.W. 1925. The oxalic acid - uranyl sulfate ultraviolet radiometer. J. Amer Chem.Soc., 47, 718-25.

ATKINS, W.R.G., 1926. A quantitative consideration of some factors concerned in plant growth in water. J du Conseil Internat. pour l'Exploration de la Mer, 1, 99-126.

ATKINS, W.R.G., and POOLE, H.H. 1926 Photo-electric measurements of illumination in relation to plant distribution. Pt.I. Sci.Proc R.Dublin Soc., 18, 277-298, (No 25) and Notes, Botany School, Trinity College, Dublin.

1929, 1. The integration of light by photo-electrolysi Loc.cit., 19, 159-164, (No 16)

1929, 2. The photo-electric measurement of the illumination in buildings. Loc.cit., 19, 173-188, (No.18).

1929, 3. Photo-electric measurements of illumination in relation to plant distribution. Pt.II. Measurement with portable galvanometers. Loc.cit., 19.

1929, 4. The photo-chemical and photo electric measurement of the radiation from a mercury vapour lamp. Loc. cit., 19.

1929, 5. The uranyl oxalate method of daylight photometry and its photo-electric standardization Loc cit , 19

BACON, R.F. 1907. Catalysis by means of uranium salts in sunlight.

Philippine J. of Sc.A2, 129-138.

1910. A solution of oxalic acid and uranium salts as a chemical photometer.

Loc.cit. A5, 281-304.

BÜCHI, P.F. 1924. Die Quantenempfindlichkeit der Uranyloxalatphotolyse. Z.f Phys.Chem. III, 269-314

BURNS, G.R. 1923. Studies in tolerance of New England forest trees. IV. Minimum light requirement referred to a definite standard. Vermont Agric Expt Sta Bull 235,pp.32.

BURNS, G.R. 1927. Id.VI. A portable instrument for measuring solar radiation in forests. Loc.cit.Bull, 261, pp.30.

CASE, T.W. 1921. Strontium photo-electric cell. A new photo-electric cell. Case Research Lab. (Auburn N.Y.) Bull, No.3. [Not mentioned in text].

DORNO, C.1919. Physik der Sonnen-und Himmelsstrahlung.

FORREST,J.F. 1913. The electric arc as a standard. Electrician, 71, 729 and 1007.

GENERAL ELECTRIC CO. RESEARCH STAFF. 1924. Photo-electric and selenium cells. Nature, 113, 606,(April 26).

GILLAM, A.E., and MORTON, R.A. 1927. A comparison of certain methods for determining the ultra-violet intensity of a light source. J. Soc. Chem.Ind., 46, 417-420 T.

1928. The deterioration of quartz mercury vapour lamps and the luminescence of transparent fused quartz. Phil. Mag., Ser.7, 6, 1123-1132.

HILL, L. 1927. Measurement of the biologically active ultra-violet rays of sunlight. Proc.Roy. Soc.B.102, 119-127, and WEBSTER, HILL and EIDINOW, Lancet, 206, 745 (April, 1924).

KISTIAKOWSKY,G.B. 1928. Photochemical processes. New York.

KLUGH, A.B. 1925. Ecological photometry and a new instrument for measuring light. Ecology, 6, 203-237.

LUCKIESH 1915. Color and its applications. New York.

LUCKIESH 1922. Ultra-violet radiation. New York.

LUNDEGÅRDH,H. 1925. Klima und Boden in ihrer Wirkung auf das Pflanzenleben, Jena.

NIEPCE de SAINT VICTOR et CORVISART,L. 1859. De la fécule végétale et animale sous le rapport de l'influence transformatrice qu'exercise surelle la lumière solaire; de la dextrine, du sucre de canne, de l'acide oxalique sous le même rapport; de quelques substances qui annihilent on accioissent cette action solaire. C.R. Acad. Sci. Paris, 49, 368-371.

PATERSON, C.C., and WALSH, J.W.T. 1915. First report of the Departmental Committee on lighting in factories and workshops. 1, 63. Quoted from Photometry and illumination, J.W.T.W., Dictionary of applied physics. Glazebrook 1923, 4, 448.

POOLE, H.H. 1925. On the photo-electric measurement of submarine illumination. Sci.Proc.Roy. Dublin Soc. 18, 99-115.

POOLE, H.H., and ATKINS, W.R.G. 1926. On the penetration of light into sea-water. J. Marine Biol. Assoc., 14, 177-198.

1928. Further photo-electric measurements of the penetration of light into sea-water. Loc. cit. 15, 455-483.

1929. Photo-electric measurements of submarine illumination throughout the year. Loc.cit., 16, 297-324.

POOLE, J.H.J. 1928. A simple form of photo-electric photometer, using a neon lamp to measure the current. Sci.Proc.Roy.Dublin Soc., 19, 17-25, (No.3).

RUBEL, E., 1928. Lichtklima und Lichtgenuss. Abderhalden's Handbuck der biol. Arbeitsmethoden. Abt.XI. Teil 5. Heft. 1, 233-292. Lieferung 279.

SCOTT,W.W., and DERBY,W.G., 1922. [See Scott, Standard methods of chemical analysis 2nd. edition New York].

SEGELKEN, J.G. 1929. The determination of light intensity. Ecology, 10, 294-297.No.3, July[Received too late for mention in text]

SHELFORD,V., and GAIL, F.W. 1922. A study of light penetration into sea water made with the Kunz photo-electric cell, with particular reference to the distribution of plants. Publ.Puget Sound Biol. Sta., 3, 141-176.

1929. Use of photo-electric cells for light measurement in ecological work. Ecology, 10, 298-311, No.3, July. [Received too late for mention in text],

TONNEY, F.O., SOMERS, P.P., and MARTI,W.C. 1928. Actinic measurement of solar ultra violet light and some correlations with the erythema dose. J.Preventive Medicine, 2, 493-511 (No.6).

WIESNER, J. 1907. Der Lichtgenuss der Pflanzen Liepzig.

ZEDERBAUER, E. 1907. Das Lichtbedürfniss der Waldbäume und die Lichtmess Methoden-Centralb. F. d. ges Forstwesen. Hft. 8 and 9, 325-330. [Trans. by R.Zon and B.T. Boisen, Forestry Quarterly, 1908, 6, 254-262.]